

IMPRINT-FREE CODING FOR FERROELECTRIC NONVOLATILE COUNTERS

FIELD OF THE INVENTION

The present invention relates to coding methods, and more particularly,
5 to a coding method that substantially reduces imprint when used in conjunction
with ferroelectric nonvolatile counters.

BACKGROUND OF THE INVENTION

Ferroelectric materials such as lead-zirconate-titanate ("PZT") can be
used as the dielectric material in a ferroelectric capacitor that in turn is used as
10 the memory element in a nonvolatile memory cell, latch, or counter. In order
to be useful as the memory element in a semiconductor nonvolatile memory,
latch, or counter, however, a ferroelectric capacitor must retain data for an
extended period of time at a given storage temperature. The ability to retain
data, also known as retention performance, is adversely affected by a multi-
15 faceted mechanism known generally by those skilled in the art as "imprint".
The term imprint is used because it implies that the history of the data stored in
the ferroelectric capacitor affects its present retention performance.
Specifically, storage or writing of data of the same binary value for a long
period of time at temperature undesirably degrades the ability of the
20 ferroelectric capacitor to retain data of the opposite binary value.

In a ferroelectric nonvolatile counter, the most significant bits stay at a
logic zero data state until the count number is large enough to flip the logic

state to a logic one data state, if conventional binary coding methods are used. For a counter with a large number of bits, the most significant bits are written (clocked) to the logic zero data state many times before they are eventually written to a logic one data state. For example, in a 40 bit counter, the most significant bit is written to a logic zero data state 2^{39} times, which is about 10^{12} times, before it is finally written to a logic one data state. Thus, this most significant bit and the associated nonvolatile ferroelectric capacitor is very significantly imprinted to the logic zero data state, and the imprinting will therefore negatively impact its ability to retain the logic one data state.

Turning now to FIG. 1, a prior art conventional five-bit binary coding scheme is shown. Note that while the least-significant bit ("LSB") switches with every advancement of the count, the most-significant bit ("MSB") does not switch until sixteen zero data states have been written to the associated ferroelectric capacitor. Of course, the imprint problem increases for the most-significant bits as the total number of bits in the counter increases.

What is desired, therefore, is a novel coding scheme in which none of the counter bits is repeatedly forced to the same data state, but is frequently switched so that the undesirable performance degradation due to imprint can be minimized.

SUMMARY OF THE INVENTION

According to the present invention, a coding method suitable for use with ferroelectric or other nonvolatile counters subject to imprint ensures that all of the bits in the code are frequently switched and not left in a fixed data state. The general coding equation for this method is such that: for an even integer n , the output code is represented by the conventional binary code of $n/2$; for an odd integer n , the output code is represented by the conventional

binary code of the one's complement of $(n - 1)/2$. Using the coding method of the present invention, every bit switches to its complement when counting from an even number to an odd number. Since every bit switches at least once every two counts, imprint is substantially reduced. Unlike conventional binary coding, the maximal number is encoded to 1000, instead of 1111, in a four-bit coding scheme.

In addition to the method of the present invention, a digital encoder is disclosed including a XNOR gate, a "plus one" operation logic block, and a two-to-one multiplexer for converting an inverted input signal into an encoded output signal. The digital encoder also includes "up/down" and most-significant bit inputs.

The foregoing and other features, utilities and advantages of the invention will be apparent from the following more particular description of an embodiment of the invention as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a logic table illustrating a five-bit prior art conventional binary coding scheme that can lead to an imprint problem for a nonvolatile ferroelectric counter;

FIG. 2 a logic table of an encoding scheme according to the present invention suitable for use with a four-bit ferroelectric counter in which imprint effects can be minimized;

FIG. 3 a logic table of an encoding scheme according to the present invention suitable for use with a five-bit ferroelectric counter in which imprint effects can be minimized; and

FIG. 4 is a schematic diagram of an encoder according to the present invention including a XNOR gate, a “plus one” operation block, and a two-to-one multiplexer for converting an input signal into an encoded output signal.

DETAILED DESCRIPTION

5 The general equation for the coding method of the present invention is given by equation (1):

$$n \Rightarrow \begin{cases} \text{Conventional Binary Code of } \left(\frac{n}{2}\right) & \text{if } n \text{ is even} \\ \text{Conventional Binary Code of } \overline{\left(\frac{n-1}{2}\right)} & \text{if } n \text{ is odd} \end{cases} \quad (1)$$

For an even integer n , the encoded output is represented by the
10 conventional binary code of $n/2$; for an odd integer n , the encoded output is represented by the conventional binary code of the one's complement of $(n - 1)/2$. Applying this method to a four-bit counter, for example, we have the encoding output 20 shown in FIG. 2 (Table I). Every bit switches to its complement when counting from an even number to an odd number. Thus, imprint is substantially
15 reduced. Note that unlike conventional binary coding, the maximal number is encoded to 1000, instead of 1111, in the case of a four-bit counter. Applying this method to a five-bit counter, for example, we have the encoding output 22 shown in FIG. 3 (Table II). Every bit switches to its complement when counting from an even number to an odd number. Thus, imprint is substantially reduced. Note that
20 unlike conventional binary coding, the maximal number is encoded to 10000, instead of 11111, in the case of a five-bit counter.

The implementation of the counter with this encoding method is as simple as that with a binary encoding. Tables III and IV show the logic expressions for counting up and counting down for an m -bit counter.

Assume n is expressed by $d_m d_{m-1} d_{m-2} \dots d_1 d_0$ with this coding method.

5 Then:

Table III. Counting up from $n = d_m d_{m-1} d_{m-2} \dots d_1 d_0$

n		$n + 1$
n is even, i.e. d_m is 0	\Rightarrow	$n + 1 = \bar{d}_m \bar{d}_{m-1} \bar{d}_{m-2} \dots \bar{d}_1 \bar{d}_0$
n is odd, i.e. d_m is 1	\Rightarrow	$n + 1 = \bar{d}_m \bar{d}_{m-1} \bar{d}_{m-2} \dots \bar{d}_1 \bar{d}_0 + 1$

Table IV. Counting down from $n = d_m d_{m-1} d_{m-2} \dots d_1 d_0$

n		$n - 1$
n is even, i.e. d_m is 0	\Rightarrow	$n - 1 = \bar{d}_m \bar{d}_{m-1} \bar{d}_{m-2} \dots \bar{d}_1 \bar{d}_0 + 1$
n is odd, i.e. d_m is 1	\Rightarrow	$n - 1 = \bar{d}_m \bar{d}_{m-1} \bar{d}_{m-2} \dots \bar{d}_1 \bar{d}_0$

10 It should be mentioned that with the coding method of the present invention, the output is kept at zero when counting down from zero, instead of rolling over to the maximal number. Similarly, the output is kept at the maximal number when counting up from the maximal number, instead of rolling over to zero. These properties may be desired in some applications.

15 From Table III and IV, we can see that another advantage of this coding is that only the “+1” operation is needed for both counting up and counting down. An example of a circuit implementation for an m -bit encoder suitable for use in an m -bit ferroelectric counter is shown in FIG. 4 and discussed in further detail below.

Referring now to FIG. 4, a digital logic circuitry implementation of an encoder 30 is shown using the coding method of the present invention. The bold lines in FIG. 4 represents a bus having a width of m bits. Pin U/D on node 38 is set to a logic one for counting up and a logic zero for counting down. The signal on node 40, $d<m>$, is the most significant bit of the input number. The output $dout<m:0>$ is the result of counting up or counting down from $d<m:0>$. The signal on node 42, $\bar{d}<m:0>$ is an inverted input signal or the one's compliment of $d<m:0>$.

Encoder 30 includes a "plus-one" operation block 34, which can be implemented using digital combinatorial circuitry as is known by those skilled in the art. The input of block 34 receives the inverted digital input signal $\bar{d}<m:0>$, and the output of block 34 provides the output signal equal to $\bar{d}<m:0> + 1$. A first input of the two-to-one multiplexer 36 receives the inverted input signal $\bar{d}<m:0>$, and a second input receives the output signal $\bar{d}<m:0> + 1$ on output node 46. A XNOR gate 32 has a first input for receiving an up-down ("U/D") signal on node 38, a second input for receiving a most-significant bit input signal (" $d<m>$ ") on node 40, and an output 48 for providing a control signal to multiplexer 36. The output signal $dout<m:0>$ of the encoder 30 is provided at multiplexer output node 50. The output signal is equal to \bar{d} if the control signal on node 48 is a logic zero, and is equal to $\bar{d} + 1$ if the control signal on node 48 is a logic one.

If desired, the output signal on node 50 can be input to m ferroelectric latches in parallel in an m -bit counter, corresponding to the width of the m -bit bus. For example a counter having four or five ferroelectric latches corresponding to the coding schemes shown in FIGS. 2 and 3 can be used. The complemented output of the latches can be fed back to node 42 to complete a

ferroelectric counter including encoder 30. Other implementations of a full *m*-bit ferroelectric counter are also possible in which imprint effects can be minimized.

A presently preferred embodiment of the present invention and many of its improvements have been described with a degree of particularity. It should
5 be understood that this description has been made by way of example, and that the invention is defined by the scope of the following claims.